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Comparison of parallel wind measurement with Sonic and Cup-Vane at nine locations for climatological applications

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Chapter 1

Introduction

The Royal Netherlands Meteorological Institute (KNMI) uses cup anemometers and wind vanes to measure wind speed and direction, meeting WMO and ICAO requirements concerning the accuracy of wind measurements.

These sensors require a large amount of maintenance and occasionally anemometers freeze during calm winter situations. Therefore, the use of alternative wind sensors is considered. Sonic anemometers, in this report referred to as sonics, have no moving part, which makes them robust and almost maintenance free. The present cup/vane is shown in figure 1, the inset shows the Thies 2D sonic. Several tests of sonic anemometers in various environments have been performed, the results showed that they can be considered for operational use, full details are reported by Wauben, 2007.

Figure 1. The wind mast at Hupsel equipped with a sonic wind sensor and the operational KNMI cup anemometer and wind vane. The inset shows the Thies 2D sonic.

For nine locations (IJmuiden, Schiphol, Vlieland, De Bilt, Hupsel, Vlissingen, LE Goeree, Cabauw and Volkel) parallel wind measurements with conventional cup-vane anemometers and the sonic were made starting in 2009. An overview of meteorological staions is presented in figure 2. These measurements are used in this report to compare the output of the two anemometers on order to verify that the Thies 2D sonic is suitable for operational use and to investigate possible effects of the sensor change on the wind products for climatological applications.

Figure 2. Meteorological stations in the Netherlands.

Chapter 2

Data

Data from cup/vane and sonic for every ten-minute period was received from KS-KA-Klimaatdesk. In table 1 details of the sensor-indentity, period of parallel measurements and data availability (%) are presented for the stations used for analysis, figure 2 shows the locations in the Netherlands. Data were omitted whenever one of the elements of one of the sensors was missing.

Name and number	Code Cup/vane	Code Sonic	Start	Stop	%useddata
IJmuiden 225	A225 a	A225sw	20090819	20100930	99
Schiphol 240	VAM18Rtw	VAM18Rsw	20090720	20100930	99
Vlieland 242	KVLpres	KVLwind	20091201	20100930	99
De Bilt 260	A260a	A260sw20m	20091118	20101231	99
Hupsel 283	A283a	A283sw	20090629	20100930	99
Vlissingen 310	A310a	A310b	20091201	20100930	99
LE Goeree 320	320-sc1	320sw	20091223	20109230	99
Cabauw 348	A348a	A348st	20090720	20100930	98
Volkel 375	24Rt	24obsRt	20091201	20100930	99

Table 1. Stations, sensor-code and measurement period.

The 10-minute parameters used for analysis were:
DD: Mean wind direction
FF: Mean wind speed at 10 meters
FSD: Standard deviation of mean wind speed
FX: Maximum gust at 10 meter
The data used were analysed with the statistical toolpack in Excel 2007.

Chapter 3

Comparison

3.1 Wind direction, speed and gust

In tables 2-10 an overview is presented of the statistical analysis for wind direction (DD in degrees), wind speed and wind gust (FF and FX in m/s) per station during the mentioned periods from both sensors. The table shows per station the number of data, the average, 5 and 95 percentile, minimum and maximum values and standard deviation. In the last three columns the difference between cup/vane and sonic (cup/vane minus sonic) value is listed. Table 11 is a summary for all stations.

IJmuiden	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	58006	58006	58006	58006	58006	58006			
Minimum	0,0	0,0	0,0	0,0	0,1	0,3	0,0	-0,1	-0,3
5-percentile	22,2	2,1	2,8	16,0	2,2	2,9	6,2	-0,1	-0,1
Average	183,7	6,7	8,4	180,0	6,8	8,6	3,7	-0,1	-0,2
95-percentile	340,8	13,3	16,3	330,0	13,4	16,5	10,8	-0,1	-0,2
Maximum	359,9	23,5	30,4	359,9	24,2	31,0	0,0	-0,7	-0,6
SD	100,6	3,4	4,1	100,6	3,4	4,2	0,0	0,0	-0,1

Schiphol	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	62890	62890	62890	62890	62890	62890			
Minimum	0,0	0,0	0,0	0,0	0,1	0,2	0,0	-0,1	-0,2
5-percentile	15,7	1,1	1,7	14,6	1,2	1,8	1,1	-0,1	-0,1
Average	188,6	4,6	6,5	187,5	4,6	6,6	1,1	0,0	-0,1
95-percentile	341,5	9,1	12,8	336,7	9,1	12,9	5,2	0,0	-0,1
Maximum	359,9	19,3	26,0	359,9	19,7	26,7	0,0	-0,4	-0,7
SD	100,9	2,5	3,5	100,0	2,5	3,5	0,9	0,0	0,0

Vlieland	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	43399	43399	43399	43399	43399	43399			
Minimum	0,0	0,0	0,2	0,0	0,1	0,3	0,0	-0,1	-0,1
5-percentile	17,0	2,4	3,0	14,3	2,5	3,1	2,7	-0,1	-0,1
Average	187,0	7,0	8,5	182,0	7,1	8,6	5,0	-0,1	-0,1
95-percentile	340,8	12,7	15,5	336,3	12,9	15,6	4,5	-0,2	-0,1
Maximum	359,9	19,3	26,0	359,9	19,7	26,7	0,0	-0,4	-0,7
SD	100,9	2,5	3,5	100,0	2,5	3,5	0,9	0,0	0,0

De Bilt	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	58395	58395	58395	58395	58395	58395			
Minimum	0,0	0,0	0,0	0,0	0,1	0,2	0,0	-0,1	-0,2
5-percentile	21,4	0,9	1,4	22,9	1,0	1,5	-1,5	-0,1	-0,1
Average	188,6	4,6	6,5	187,5	4,6	6,6	1,1	0,0	-0,1
95-percentile	335,4	6,1	10,3	333,7	6,1	10,4	1,7	0,0	-0,1
Maximum	359,9	13,0	21,1	359,9	13,3	21,4	0,0	-0,3	-0,3
SD	101,4	1,7	2,9	101,3	1,7	2,9	0,1	0,0	0,0

Hupsel	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	65841	65841	65841	65841	65841	65841			
Minimum	0,0	0,0	0,0	0,0	0,1	0,2	0,0	-0,1	-0,2
5-percentile	19,8	0,8	1,2	16,9	0,9	1,3	2,9	-0,1	-0,1
Average	185,6	3,2	5,1	182,6	3,3	5,1	2,9	-0,1	0,0
95-percentile	336,3	6,5	10,1	332,4	6,5	10,1	3,9	0,0	0,0
Maximum	359,9	22,7	29,2	359,9	22,7	29,4	0,0	0,0	-0,2
SD	95,0	1,8	2,8	95,4	1,8	2,8	-0,4	0,0	0,0

Vlissingen	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	43341	43341	43341	43341	43341	43341			
Minimum	0,0	0,1	0,3	0,0	0,2	0,4	0,0	-0,1	-0,1
5-percentile	15,7	1,1	1,7	14,6	1,2	1,8	1,1	-0,1	-0,1
Average	179,9	5,2	7,0	176,7	5,7	7,5	3,2	-0,5	-0,5
95-percentile	341,5	9,1	12,8	336,7	9,1	12,9	4,8	0,0	-0,1
Maximum	359,9	17,3	22,8	359,9	18,9	24,6	0,0	-1,6	-1,8
SD	107,5	2,6	3,4	107,3	2,8	3,6	0,2	-0,2	-0,2

LE Goeree	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	40089	40089	40089	40089	40089	40089			
Minimum	0,0	0,0	0,3	0,4	0,2	0,4	0,0	-0,2	-0,1
5-percentile	19,7	1,9	2,4	16,8	2,0	2,5	2,9	-0,1	-0,1
Average	178,9	6,9	8,2	175,4	7,0	8,3	3,5	-0,1	-0,1
95-percentile	337,5	12,8	15,4	335,2	12,9	15,4	2,3	-0,1	0,0
Maximum	359,9	21,9	27,3	359,9	22,2	28,5	0,0	-0,3	-1,2
SD	105,9	3,3	3,9	106,7	3,3	3,9	-0,8	0,0	0,0

Cabauw	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	61660	61660	61660	61660	61660	61660			
Minimum	0,0	0,0	0,0	0,0	0,1	0,2	0,0	-0,1	-0,2
5-percentile	16,1	1,1	1,6	15,6	1,1	1,6	1,5	0,0	0,0
Average	185,9	4,0	5,7	184,2	4,0	5,7	1,7	0,0	0,0
95-percentile	337,4	8,1	11,5	333,8	8,2	11,6	3,6	-0,1	-0,1
Maximum	359,9	16,8	23,7	359,9	16,5	25,8	0,0	0,3	-2,1
SD	98,5	2,2	3,1	98,3	2,2	3,1	0,2	0,0	0,0

Volkel	DD-cup	FF-cup	FX-cup	DD-sonic	FF-sonic	FX-sonic	delta-DD	delta-FF	delta-FX
Data	43479	43479	43479	43479	43479	43479			
Minimum	0,0	0,0	0,0	0,0	0,1	0,2	0,0	-0,1	-0,2
5-percentile	21,5	0,8	1,2	20,6	0,8	1,2	0,9	0,0	0,0
Average	188,9	3,5	5,2	186,4	3,4	5,1	2,5	0,1	0,1
95-percentile	341,2	7,2	10,6	338,9	6,9	10,2	2,3	0,3	0,4
Maximum	359,9	18,3	26,7	359,9	17,5	25,9	0,0	0,8	0,8
SD	101,7	2,0	3,0	101,8	1,9	2,8	-0,1	0,1	0,2

Tables 2-10. Summary per station

All stations	average delta DD	average delta FF	average delta FX
5-percentile	2,0	-0,1	-0,1
50-percentile	2,7	-0,1	-0,1
95-percentile	4,3	-0,1	-0,1
standarddeviation	0,01	0,0	0,0

Table 11. Summary with average differences (cup/vane minus sonic) for all stations.

The results in table 2-10 show that there is a typical offset in the winddirection of about 3 degrees with a maximum of 5 degrees for Vlieland, which is probably caused by a missalignment of the sensor (information from Wauben). The sonics report on average a slightly higher (typical 0,1 m/s) wind speed and gust than the cup anemometer except Volkel where the sonic report lower value and at Vlissingen where the averaged difference is 0,5 m/s.

From the summary of the average differences in table 11 it is concluded that these parallel measurements indicate differences in wind direction and wind speed and gust when sensors are replaced from cup/vane to sonic, far less than WMO-requirements of 10 degrees and 0,5 m/s.

The correlation and RMS (root-mean-square) of the differences between DD, FF end FX from cup and sonic in the mentioned period per station are listed in tables 12-13.

The correlations and RMS indicate acceptable differences between the measurements of two instruments, but with reduced values for the wind direction for station De Bilt and Volkel. The reason for these outliers is not understood, maybe the high local roughness in combination with more light wind causes more deviations between simultaneous measurements without obvious effect on the distribution, average wind and extremes and/or the effects of sampling around the north. Wauben found that RMS De Bilt decreases to 12 degrees if these effects are taken into account.

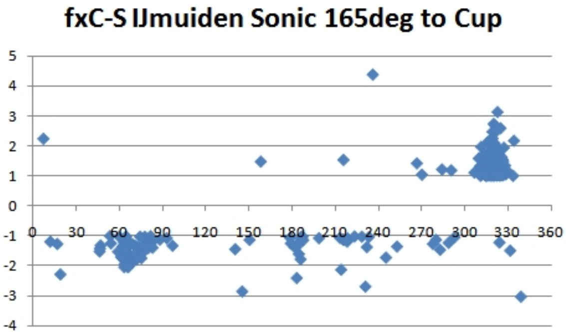
In the appendix probability distribution plots of DD, FF and FX are shown.

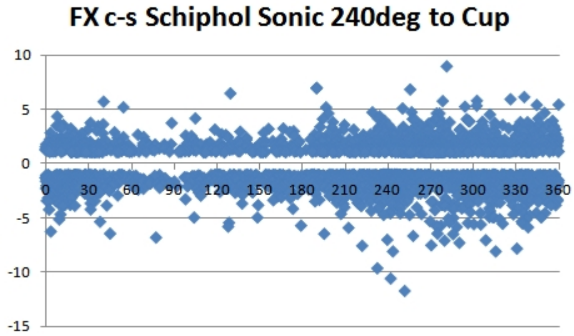
Correlation	DD	FF	FX
IJmuiden (225)	0,92	0,99	0,99
Schiphol (240)	0,96	0,99	0,98
Vlieland (242)	0,90	0,99	0,99
De Bilt (260)	0,87	0,99	0,99
Hupsel (283)	0,94	0,99	0,99
Vlissingen (310)	0,94	0,99	0,99
LE Goeree (320)	0,92	0,99	0,98
Cabauw (348)	0,95	0,98	0,98
Volkel (375)	0,87	0,96	0,96

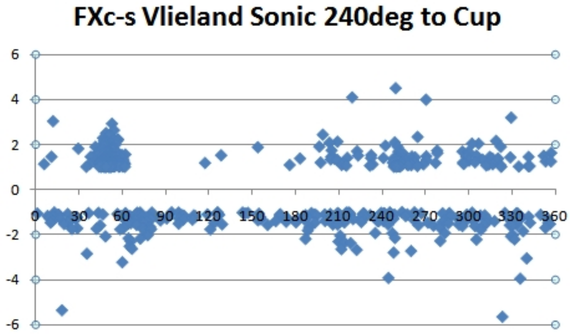
RMS	DD	FF	FX
IJmuiden (225)	41,15	0,20	0,23
Schiphol (240)	27,88	0,17	0,76
Vlieland (242)	42,28	0,24	0,31
De Bilt (260)	50,95	0,26	0,47
Hupsel (283)	31,55	0,11	0,06
Vlissingen (310)	35,91	0,55	0,58
LE Goeree (320)	41,02	0,42	0,50
Cabauw (348)	32,39	0,42	0,61
Volkel (375)	52,50	0,58	0,87

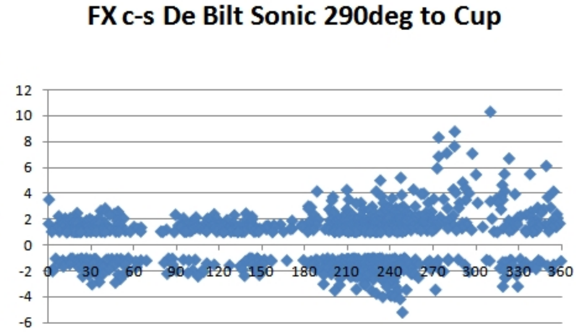
Tables 12-13. Correlation and RMS for wind direction, speed and gust per station

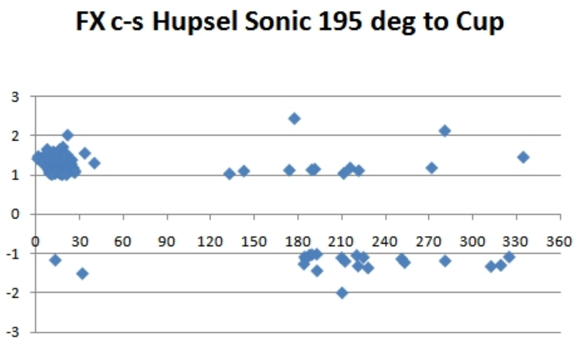
As both instruments were placed on the same mast at short distance, wake effect for wind gust is examined for speed differences between cup and sonic of at least 1 m/s, in the figures the position of the sonic relative to cup/vane is indicated. The figures indicate maximum wake effects when the winddirection is from cup to sonic.

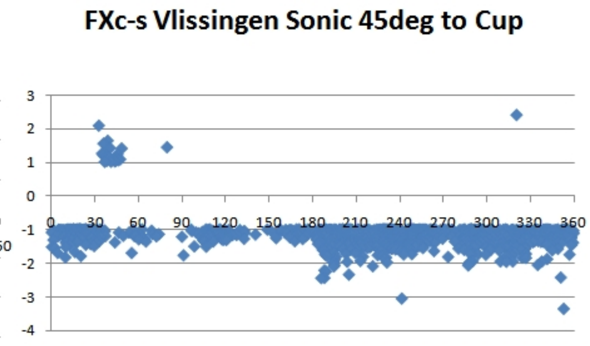


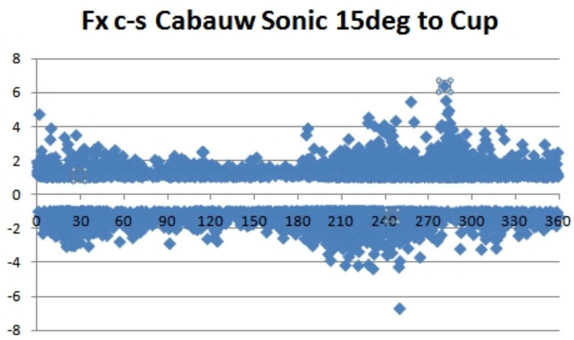


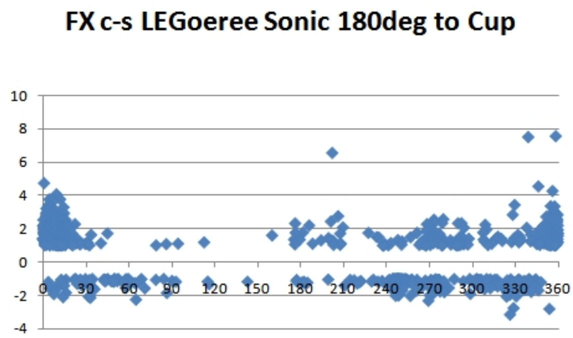


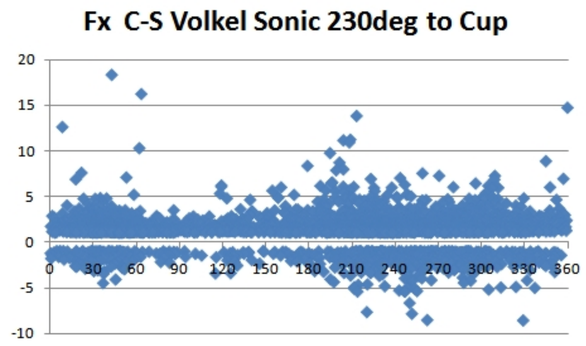












Figures 4-12

This analysis does not indicate significant differences in wind climatology after replacement by sonic anemometers.

3.2 Surface roughness

Wind speed measurements are affected by the local surface roughness of the terrain surrounding the measurement area and enlarg the ratio of wind gust over wind speed and its standard deviation.

The surface roughness generally depends on the wind direction and may vary with season due to changes in the foliage. The surface roughness is estimated from the wind data obtained for the sensors, either by indirect analysis of turbulence from gustiness (gust/mean) from hour-data (Wieringa and Rijkoort, 1983), (Verkaik, 1999) or by a direct way (sigma/mean) from ten-minute-data (Wever and Groen, 2009). Full details are available in the report WR2009-02 “Improving potential wind for extreme wind statistics” (Wever and Groen, 2009).

The theory states that the vertical temperature profile is assumed to have a neutral stratification when the average wind speed over land is more than 4 m/s. This stratification enhances a logarithmic vertical wind profile, in which the effects of local roughness at a blending height of 60 m are negligible. The wind speed at the blending height can in turn be used to compute a wind at 10 m at a hypothetical measuring site with open terrain (grass) with a typical roughness length of 3 cm. The resulting wind is referred to as potential wind and the ratio between the potential wind speed (Up) and the measured wind speed (Um) is the exposure correction factor (ECF).

For station Schiphol the ECF 2004-2008 is shown in figure 13.

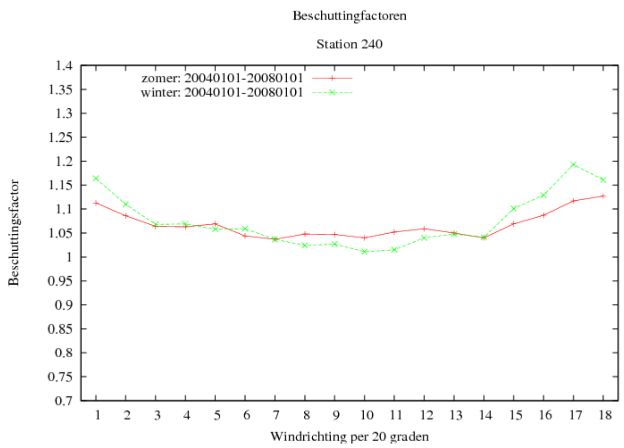


Figure 13. Exposure correction factors (per 20 degrees winddirection)
Schiphol summer and winter, 2004-2008.

With the measurements of the standard deviation and the average wind per ten minutes, the changes in ECF due to sensor replacement can be estimated with the standard deviation (SD) divided by the mean wind speed from both sensors, sonic and cup/vane. Dividing these two per ten minutes and taking the median results in an indication for the rate of change of ECF due to sensor-replacement.

For Schiphol this factor $(\frac{\sigma_u}{U})_{vane}/(\frac{\sigma_u}{U})_{sonic}$ has been calculated for windspeeds above 4 m/s (in order to obtain near-neutral conditions and a logarithmic windprofile). In figure 4 the X-axis indicates the number of data, the Y-axis the mentioned factor, resulting in a median value used of 1,013 (figure 14).

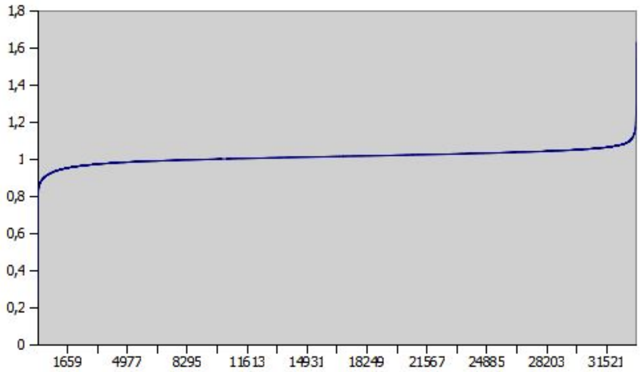


Figure 14. Example of ECF-change due sensor-replacement for Schiphol.

This example indicates a small reduction of the average exposure correction factor by less than 2 %, a small influence on the potential wind, with average windspeeds of 3-7 m/s, a 2% reduction will decrease the average potential wind speedby about 0,1 m/s. For maximum windspeeds in the order of 25 m/s, the estimated potential wind speedwill be reduced by 0,5 m/s in the calculation of potential wind from sonic measurements. For all stations table 14 summarizes the reduction of average exposure correction factor (without LE Goeree, SD not available).

station	*ECF-factor*
IJmuiden (225)	1,012
Schiphol (240)	1,013
Vlieland (242)	1,009
De Bilt (260)	0,997
Hupsel (283)	1,003
Vlissingen (310)	1,091
Cabauw (348)	0,976
Volkel (375)	0,951

Table 14. Change in exposure correction factor due to sensor change.

Generally the ECF is close to unity, but Vlissingen and volkel show deviations exceeding 1% which are probably related to the complex local surface roughness. The deviation of Cabauw is unclear. ***However, roughness analysis is complex and requires fundamental study of for instance instrumental behaviour and a separate project if potential wind calculations are to be maintained in future. It is then also recommended to maintain simultaneous measurements at five main stations for at least two years.***

3.3 Summary

The instrument replacement of cup/vane wind measurements to sonic (THIES 2D) has, based on the data in the mentioned simultaneous period, a negligibly small influence on the climatology of windseries.

Despite wake effects average wind direction deviation is far less than WMO-requirements, the deviation is around 3 degrees for wind direction, for average wind speed and gust deviate about 0,1 m/s.

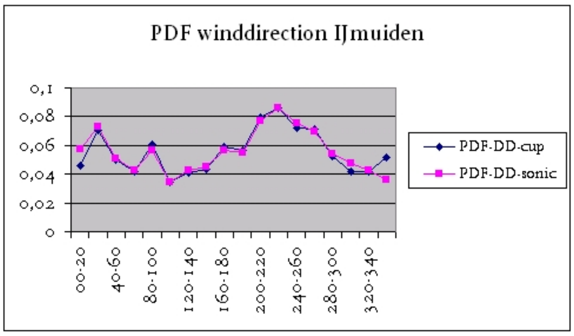
Calculations of potential wind will not significantly be effected by sensor replacement, but require fundamental study of instrumental behaviour and parallel measurements for about five main stations for at least two years on separate masts in order to avoid wake-effects.

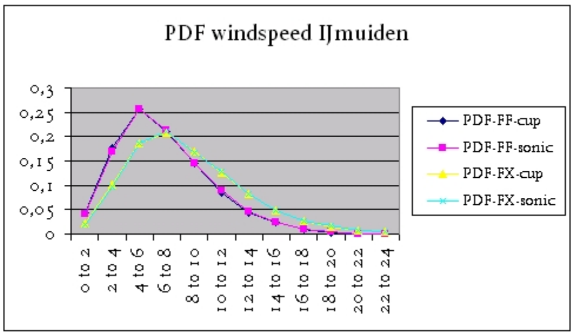
Many thanks to Wiel Wauben, Gerard van der Schrier and Theo Brandsma for support and review.

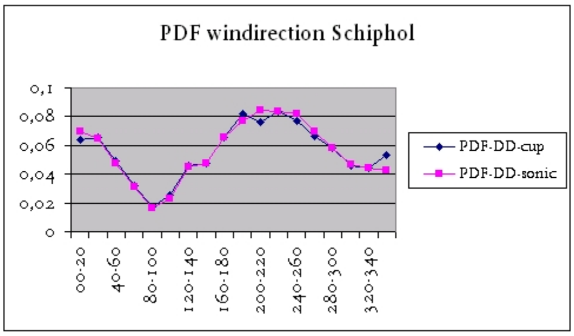
Chapter 4

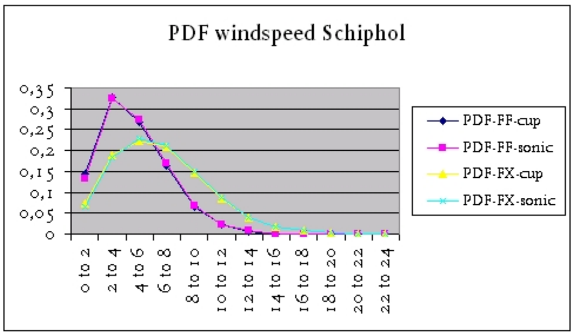
Appendix

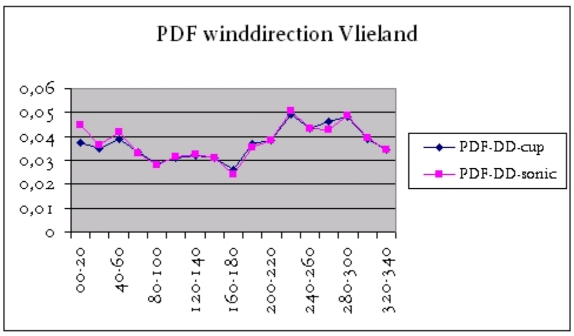
Probability distribution plots of wind direction, wind speed and gust for the nine stations indicated in figure 2 for the period mentioned before are shown in figures 15-32. The X-axis indicates either winddirection classes per 20 degrees (left) or wind speedclasses per 2 m/s (right), the Y-axis indicates the distribution per class.

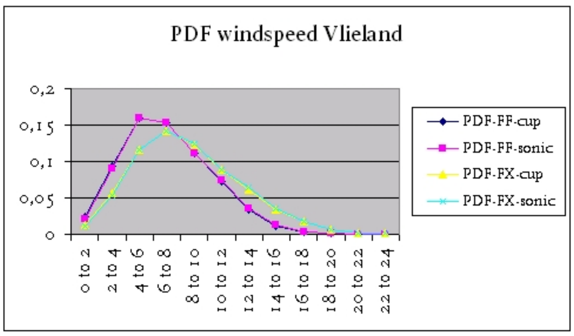


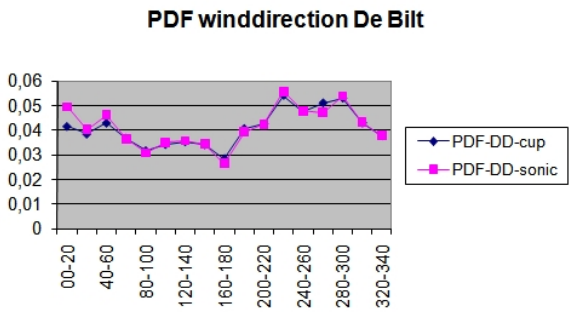








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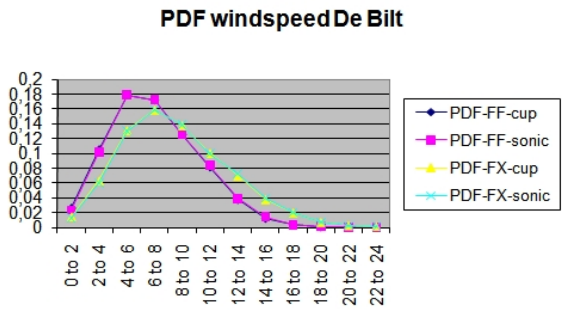
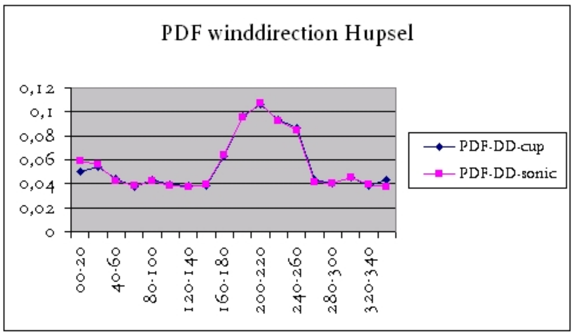
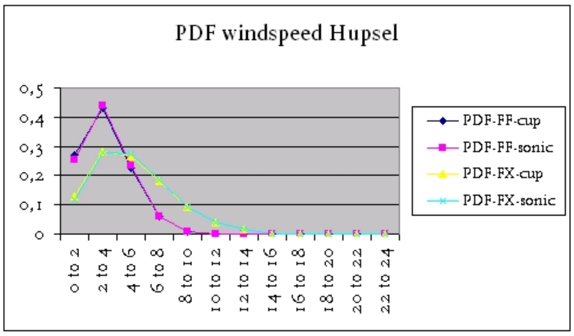
PDF-DD-cup
PDF-DD-sonic


PDF windspeed De Bilt
PDF-FF-cup
PDF-FF-sonic
PDF-FX-cup
PDF-FX-sonic


PDF winddirection Hupsel
PDF-DD-cup
PDF-DD-sonic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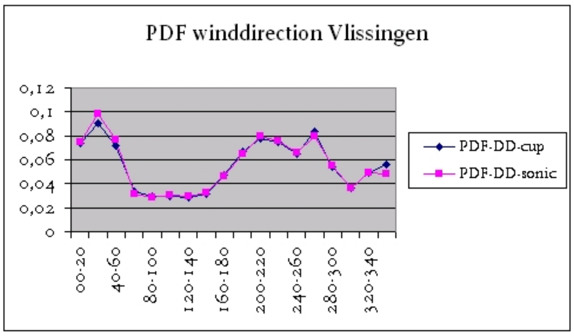
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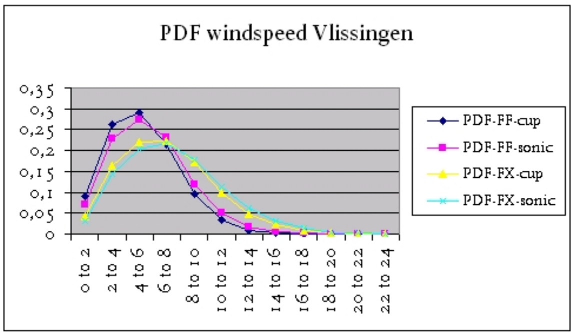
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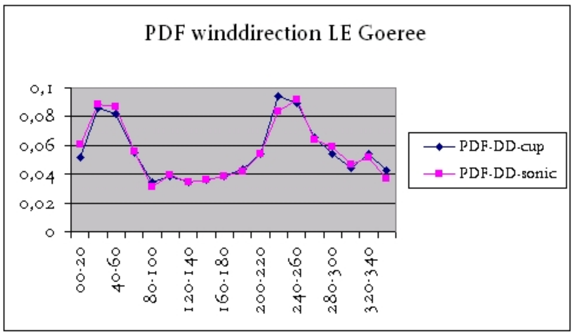
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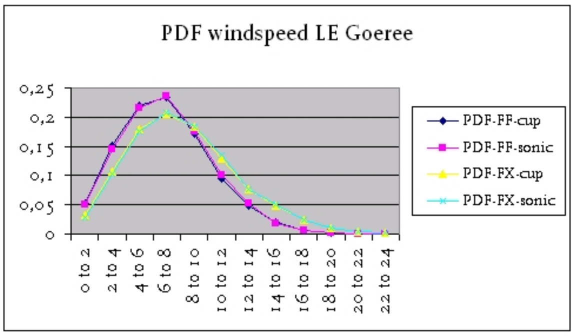
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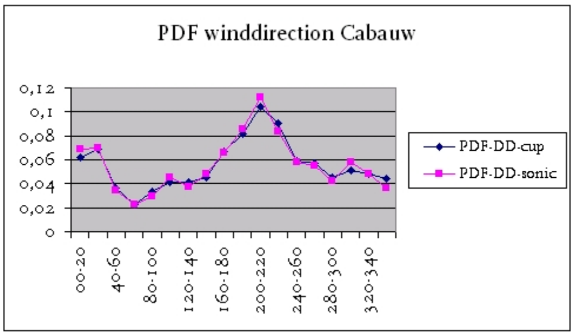
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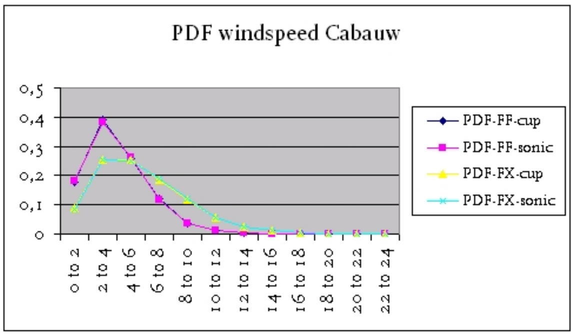
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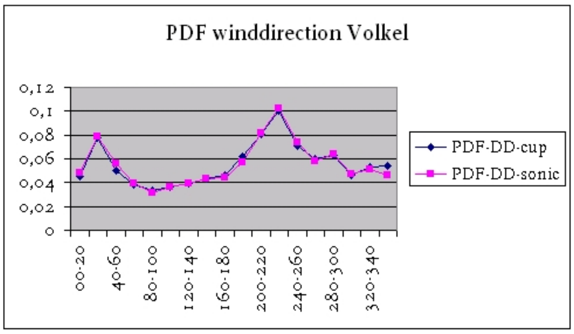

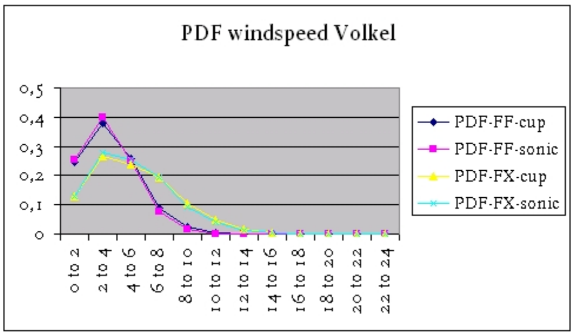

Figures 15-32: Probability distribution plots per station of winddirection, wind speed and wind gust.

Chapter 5

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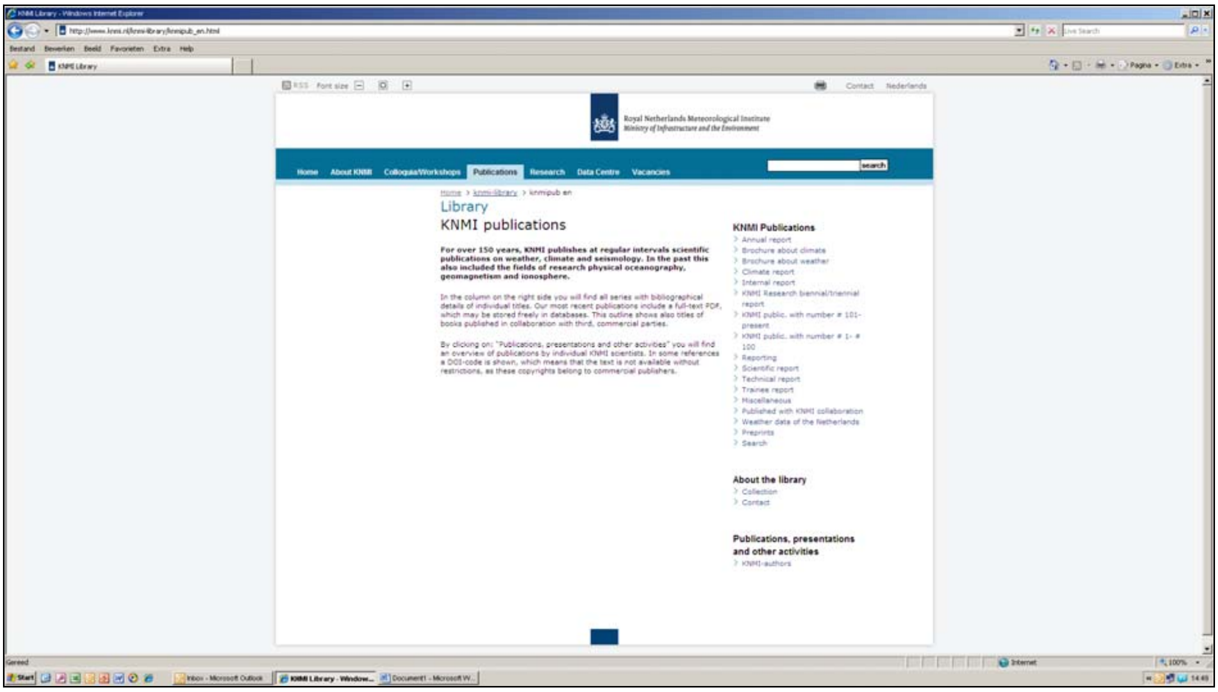
www.knmi.nl/knmi-library/knmipub_en.html



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